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A review on exergy analysis of industrial sector

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ABSTRACT

Performance analysis of industrial sector with high-energy consumption, about 30–70% of total energy use of the countries, is taken into consideration recently. A number of studies have been conducted on energy analysis of different industries and during the last decades exergy analysis applied to offer more realistic suggestions for optimization and improvement of the industrial sector. The present study reviews the existing studies on exergy analysis of industrial sector. The irreversibility and losses of industrial processes are also determined. It is concluded that industrial sector has a high potential of improving in order to reduce the energy consumption and emissions.

Contents

1. Introduction

Nowadays, industrial sector as one of the largest energy consumers is taken into accounts in several projects and researches. It was reported that 37% of the world's total delivered energy is consumed by the industrial sector [1]. The share of energy consumption of the industrial sector varies between 30% and 70% [2] based on different applications and locations. For instance, the share of energy consumption of the industrial sector of Jordan was reported to be around 31% [3], 30% for Slovenia [4], 35% for Turkey [5] and 70% for China [6].

Diversification and complexity of industrial sector, makes the calculation of the exact condition (operating temperature pressure) of each process almost impossible. Therefore, in order to analyze the performance of the industrial process based on the first and second law of thermodynamics, the operating temperature is divided into three sub-sectors of low, medium or high temperatures [7,8].

Typically, in the industrial sector, the energy flows through the different macro-system which can be named as iron–steel industry, cement industry, chemical and petrochemical industry, sugar industry, fertilizer industry, non-iron metal industry and other industries. This classification is illustrated in Fig. 1.

Exergy as a measure of the quality of energy can be considered to evaluate, analyze and optimize the industrial processes. Justifying the system's performance based on the exergy analysis is more realistic than energy analysis. To determine the importance of the

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Nomenclature

B	Exergy
CG	Cogeneration
E	Electricity
$\dot{E}x_{in}$	Exergy input (W, kW)
$\dot{E}x_{out}$	Exergy output (W, kW)
$\dot{E}x_{work}$	Exergy of work rate (W, kW)
$\dot{E}x_{Q}$	Exergy of thermal energy (kW)
$\dot{E}x_{ch}$	Chemical exergy (W, kW)
$\dot{E}x_{k}$	Kinetic exergy (W, kW)
$\dot{E}x_{p}$	Potential exergy (W, kW)
$\dot{E}x_{ph}$	Physical exergy (W, kW)
f	Fuel
h_f	Heating values
I	Irreversibility
γ_f	Exergy grade functions
η_{energy}	Energy efficiency
ψ_a	Specific exergy
ε	Exergetic efficiency

exergy analysis, energy and exergy efficiencies of some industrial processes are compared in Table 1. Exergy analysis prepares the right platform to specify the maximum performance of a system and the sources of irreversibility within the system. Since all industrial processes are irreversible, the exergy loss can be decreased by decreasing reaction rate and consequently exergy efficiency would be enhanced [10].

Recently, the interest of applying exergy analysis to different kind of systems in various sectors has been increased [12–15]. The performance evaluation of a system based on the second law of thermodynamics in the industrial sector has been done on cement [16–18], chemical industry [19] and iron–steel industry [20] much more than the others. These industries were known as the most energy intensive industries in comparison with other common industries [21]. For instance, it was observed that cement industry in Malaysia consumes around 12% of the total energy consumption of the country [22].

Being one of the largest energy consumers, determines the necessity of investigating the exergy analysis of the industrial sector. On the other hand, from the environmental point of view, the industrial sector is one of the major contributors of greenhouse gases emissions. It was reported that about one-third of the carbon dioxide emission released is associated with industrial sectors [23,24].

In the context of this work, the studies on exergy analysis of the industrial sector are reviewed. It may be reported that to the best of authors' knowledge, there is no work on the review of exergy analysis of the industrial sector. Therefore, this review is expected to fill this gap.

2. Studies conducted on exergy analysis of industrial sector

The conducted studies on exergy analysis of the industrial sector are classified into three main subsections of exergy analysis of the industrial sector of different countries, exergy analysis of different industries and exergy analysis of industrial devices.

2.1. Energy analysis of industrial sector in different countries

The exergy of the industrial sector of South Africa, which consumes about 44% of the total national energy use, was analyzed by Oladiran et al. [25]. The exergy balance and exergy efficiency equations were applied to different sub-sectors of the country, namely, iron and steel, chemical and petrochemical, mining and quarrying and non-ferrous metals. The exergy balance for the closed system was evaluated by applying Eq. (1):

$$\sum_r E^{Qr} - E^w - I = 0 \quad (1)$$

where E^{Qr} and E^w are associated with the exergies of heat transfer [7] and work and they can be calculated by Eqs. (2) and (3), respectively

$$E^{Qr} = (1 - T_0/T_r)Q^r \quad (2)$$

$$E^w = w \quad (3)$$

The exergetic efficiency of heating by fossil fuels and electricity was evaluated based on Eqs. (4) and (5), respectively [25]

$$\psi_{hf} = \frac{E^{Qp}}{m_f \varepsilon_f} \quad (4)$$

$$\psi_{he} = \frac{E^{Qp}}{E^{we}} \quad (5)$$

The maximum exergy efficiency was reported for non-ferrous metals industry, which varied from 42.7% in 1994 to 46.4% in 2003. It was also concluded that although the energy efficiency of mining and quarrying was the highest, its exergy efficiency was the least with the maximum amount of 18.5% in 2003.

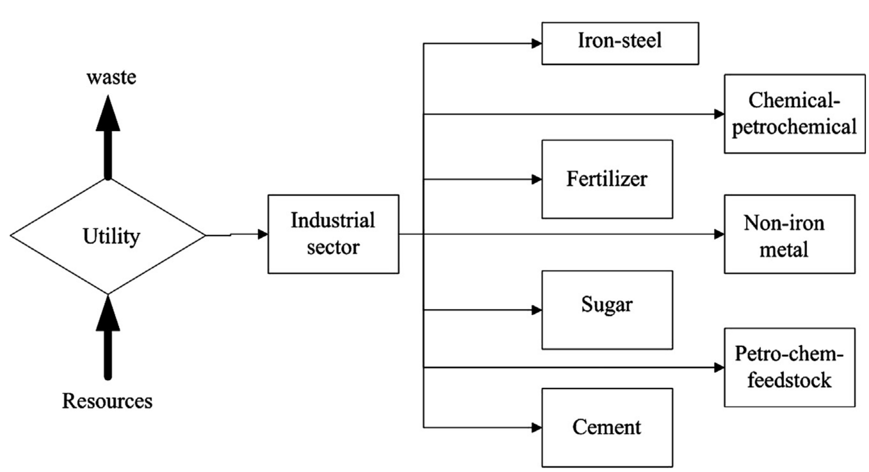

Fig. 1. Illustrative presentation of sub-systems of the industrial sector [9].

The exergy modeling technique was applied to the Turkish industrial sector over a 13 years period from 1990 to 2003 by Utlu et al. [9]. The utilized methodology in this study was similar to one which was applied by Rosen and Dincer [26]. It was concluded that the exergetic efficiency of the Turkish industrial sector changed from 29.7% to 33.2% in the analyzed period. Iron and steel industry was determined as the most exergy efficient industry.

Utju et al. [27] also conducted a parametric study to determine the effect of dead state temperatures on the exergetic efficiency of the industrial sector of Turkey. Pointing out to the fact that 42% of total energy was consumed by industrial sector, shows the importance of analyzing exergy efficiency of this sector. The total exergy input to the industrial sector of Turkey was reported to be around 1115 PJ. It is found that changing the dead state temperature from 0 to 25 °C, would lead to exergy efficiency variation from 25.3% to 29.5%.

Exergy modeling of major energy intensive industries in U.S. was developed by Al-Ghandoor et al. [28]. The general exergy balance was computed applying

$$\sum_{in} m_{in}\varepsilon_{in} - \sum_{ex} m_{ex}\varepsilon_{ex} - \sum_r E^{Qr} - E^w - I = 0 \tag{6}$$

Considering the flowing stream of matter, the specific total exergy (ε) presented in Eq. (6) can be calculated using

$$\varepsilon = \left[ke + pe + (h-h_0) - T_0(s-s_0)\right] + \left[\sum_j (\mu_{j0} - \mu_{j00})X_j\right] \tag{7}$$

To evaluate the specific exergy of fuel at environment conditions, the physical exergy became zero and the specific exergy only included the chemical exergy that can be computed by applying

$$\varepsilon_f = \gamma_f h_f \tag{8}$$

The heating values (h_f) and the exergy grade functions (γ_f) of the fuels which were considered in Al-Ghandoor et al.'s study [28] were obtained from the literature [29,30]. The reported exergy efficiency of the fuel heating processes varied between 12.1% and 39.6% for the low and high category, respectively. These percentages changed to 24.7% and 46.6% for electrical heating processes. The maximum overall exergy efficiency was reported to be 56% for inorganic industry, which follows, by 45.8% for glass industry.

The second law performance of the industrial sector of Greece was analyzed by Koroneos et al. [11] for a 14 years period. The exergy content of material resources was evaluated by using the same correlation applied by Wall [31,32], which can be written as

$$E_x = \sum_i n_i(\mu_i - \mu_{i0}) + RT_0 \sum_i n_i \ln\frac{c_i}{c_{i0}} \tag{9}$$

The exergy efficiency was defined as the ratio of work to the exergy input. The industrial exergy efficiency was reported to be 51.3% in 2003. A brief summary of investigated countries is presented in Table 2.

Table 1
Comparison between energy and exergy efficiency of selected industrial processes [11].

Industrial process	Energy efficiency (%)	Exergy efficiency (%)
Petroleum refining	90	10
Residential heating (fuel)	60	9
Domestic water heating (fuel)	40	2–3
Coal gasification	55	46

2.2. Exergy analysis of different industries

The exergy analysis of cement industry will be reviewed first in Section 2.2.1 and then the exergy analysis of chemical and petrochemical industry will be described in Section 2.2.2. Finally, the exergetic efficiency of other industries will be evaluated in Section 2.2.3

2.2.1. Exergy analysis of cement industry

The exergetic efficiency of a Trass Mill process in a cement plant was assessed by Sogut et al. [32]. The general exergy balance for the system was evaluated by using

$$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \sum \dot{m}_{in}\psi_{in} - \sum \dot{m}_{out}\psi_{out} = \Delta \dot{E}x_{system} \tag{10}$$

The term Ψ in Eq. (10) was defined as the physical exergy, which may be expressed [34]

$$\psi = (h-h_0) - T_0(s-s_0) \tag{11}$$

Different correlations were presented for calculating the exergetic efficiency [32]. It can be defined as the ratio of desired exergy to the used exergy which was named rational efficiency by Kotas [35] and Cornelissen [36]. The exergy efficiency was reported to be 10.68% for the trass mill while the exergy losses was found to be around 89%. It was also pointed out that adding the energy recovery system before the trass mill unit, would decrease the losses to 33%.

Using energy and exergy analyses, the performance of the raw mill in cement production was analyzed by Utlu et al. [37]. The exergy balance for the system was written based on Eq. (10). The total exergy input and output were reported to be 7864.73 MJ and 1981.40 MJ, respectively. The exergetic efficiency of the raw mill was computed by using

$$\varepsilon = \frac{\sum m_{out}\psi_{out}}{\sum m_{in}\psi_{in}} \tag{12}$$

The calculated overall exergy efficiency of the raw mill based on Eq. (12) was reported to be 25.2%.

The exergy of the different cogeneration power plant in the cement industry was optimized by Genetic algorithm in the study conducted by Wang et al. [38]. The single flash steam cycle, the dual pressure steam cycle, the organic Rankine cycle and the Kalina cycle performances were compared in their work. The

Table 2
Summary of the investigated countries based on the different industries.

Country	Investigated industries	Remarkable conclusion	Ref.
USA	Paper mills, steel mills, primary aluminum, iron foundries, glass, cement, petroleum, petrochemical, organic, inorganic, plastic resin, nitrogenous fertilizer.	Maximum overall exergy efficiency was reported 56% for inorganic industry which follows by 45.8% for glass industry.	[28]
South Africa	Iron and steel, chemical and petrochemical, mining and quarrying, non-ferrous metals and non-metallic materials.	Maximum exergy efficiency was reported for non-ferrous metals industry (42.37–46.37%) and minimum exergy efficiency was related to mining and quarrying industry (12.95–18.52%)	[25]
Turkey	Iron and steel, chemical and petrochemical, cement industry, sugar industry.	Maximum exergy efficiency was reported 39.48% for iron and steel industry and the minimum one was 20.42% for chemical and petrochemical industry.	[27]
Iran	Seventeen different industries have been considered for calculation of the exergy and energy efficiencies	The energy and exergy efficiencies for the entire industrial sector of Iran were approximated as 63% and 42%, respectively.	[33]

exergy efficiency of the waste heat recovery system was computed by applying

$$\eta_{ex} = \frac{E_{in} - \sum_i I_i}{E_{in}} \quad (13)$$

The total exergy efficiency was evaluated to be 42.3% for the single flash cycle, 40.9% for dual-pressure cycle, 36.6% for organic Rankine cycle and 44.9% for Kalina cycle. The major exergy destruction sources were reported to be from turbine, condenser and boilers.

2.2.2. Exergy analysis of chemical and petrochemical industry

The exergy efficiency of a central cogeneration system in a petrochemical complex was evaluated by Torres et al. [39]. The rational efficiency (second law efficiency) [35] of each sub-systems were computed. The ratio of the desired exergy effect to the exergy used to drive the process was defined as the exergetic efficiency. The maximum exergy efficiencies were dedicated to the preheaters and steam turbine, 86.22% and 81.69%, respectively. The largest exergy destruction was 81.51% that was occurred in the steam generator. Finally, the overall efficiency for the power plant cycle with and without cogeneration was compared and it was concluded that the overall efficiency varies from 8.96% for power cycle alone to 38.75% for power cycle with cogeneration.

Portha et al. [40] investigate the relation between exergy analysis and environmental impact of petrochemical processes. They considered the exergy as four components of kinetic, potential, physical and chemical. The kinetic and potential exergy of the system was assumed as negligible due to the mass flow in and out of the industrial processes [41]. The physical exergy was calculated based on Eq. (14) which was presented by Szargut et al. [29]

$$B_{ph} = H - H_0 - T_0(s - s_0) \quad (14)$$

The chemical exergy was evaluated by using the proposed correlation by Szargut [42], which is shown in

$$B_{ch} = \sum n_i b_{ch,i} \quad (15)$$

where $b_{ch,i}$ represents the partial molar exergy of the component. The exergy balance for the open system was written as

$$\dot{B}_d = \sum_{in}\left[\dot{W} + \dot{Q}\left(1 - \frac{T_0}{T}\right) + \dot{B}_{fr}\right] - \sum_{out}\sum\left[\dot{W} + \dot{Q}\left(1 - \frac{T_0}{T}\right) + \dot{B}_{fr}\right] \quad (16)$$

The maximum exergy destruction was observed in heat exchangers, 4.38 MW, which was followed by the exergy destruction in reactors, 1.63 MW. It was also concluded that the reactor's inlet temperature and the feed's composition were the most effective parameters on the exergy destruction amount.

2.2.3. Exergy analysis of other industries

The effect of the internal loop parameters on the second law-based efficiency of industrial ammonia synthesis was studied by Yordanova [43]. The exergy of material was considered as a combination of physical and chemical exergy [29]. The total exergy losses, D, was computed based on

$$D = \text{constant} + \sum_{i=1}^{n} \mathrm{E}_{i,in,en} - \sum_{j=1}^{q} \mathrm{E}_{j,useful,out,en} \quad (17)$$

The main sources of irreversibility were reported to be the irreversibility of ammonia synthesis, heat exchangers and heat recovery system. The amount of losses associated with the named sources were between 52% and 65% of the total losses. It was also concluded that the exergy efficiency would be increased as the exergy consumption by ammonia condensation decreased.

The exergy of the blast furnace in iron making and the exergy of direct iron smelting were investigated by Ostrovski et al. [10]. Fuel combustion, heat transfer and reduction reactions were determined as the main sources of exergy losses. The exergy analysis of heat transfer and combustion were found from literature and the exergy analysis of chemical reaction was calculated based on

$$\Delta\phi = \Delta H\left(1 - \frac{T_e}{T}\right) + \Delta G\left(\frac{T_e}{T}\right) \quad (18)$$

Considering the exergy of the blast furnace, the exergy efficiency was reached to 61%. The difference between the exergy of the products and coal was defined as the exergy loss.

The energy and exergy of cogeneration power plants in sugar industries were compared by Kamate et al. [44]. To determine the chemical exergy of the fuel bagasse, Eq. (19) given by Koatas [35] was used:

$$\phi_{\text{dry}} = \frac{1.0438 + 0.1882 \times (h/c) - 0.2509 \times [1 + 0.7256 \times (h/c)] + 0.0383 \times (n/c)}{1 - 0.3035 \times (o/c)} \quad (19)$$

As the bagasse used in sugar industry has a significant amount of moisture content, the chemical exergy correlation was corrected to

$$\varepsilon_0 = [\text{net calorofic value} + wh_{fg}]\phi_{dry} \quad (20)$$

The exergetic efficiency of the cogeneration plant was determined by applying

$$\eta_{Ex} = \frac{W_{CG} + \alpha Q_{CG}}{m_b \times \varepsilon_0} \quad (21)$$

Considering α as 0.260, the highest exergetic efficiency was reported to be 34.4%. The variation of total irreversibility with pressure and temperature was evaluated and it was found that increment in steam inlet pressure and temperature leads to a reduction in total irreversibility of the system. A comparison between the energy and exergy efficiencies of studied industries is presented in Table 3.

2.3. Exergy analysis of industrial devices

The exergy of an electrical-arc-furnace with 55 t casting capacity was analyzed by Çamdali et al. [45]. Exergy of work transfer,

Table 3
Comparison between energy and exergy efficiency of different industrial processes.

Process	Industry	Energy efficiency (%)	Exergy efficiency (%)	Exergy losses (%)	References
Trass mill	Cement	74	10.67	89	[32]
Raw mill	Cement	84.3	25.2	–	[37]
Cogeneration with single flash steam cycle	Cement	–	42.3	57.9	[38]
Cogeneration with dual presser steam cycle	Cement	–	40.9	59.3	[38]
Cogeneration with organic Rankine cycle	Cement	–	36.6	64.6	[38]
Cogeneration with Kalina cycle	Cement	–	44.9	57	[38]
Central cogeneration cycle	Petrochemical	88.4	38.75	–	[39]
Cogeneration power plants	Sugar	93	34.4	–	[44]

heat transfer and exergy associated with streams were considered as the main exergy transfer of the system. The kinetic, potential, physical and chemical exergies were taken into account as the exergy transfer associated with steady streams of matter. The physical exergy was computed based on Eq. (11), and the chemical exergy was calculated using

$$\varepsilon_{ch} = \sum\left[g_i(P_0,T_0) + RT_0 \ln\left(\frac{P_{io}}{P_0}\right) - g_i(P_0,T_0) + RT_0 \ln\left(\frac{P_{i00}}{P_0}\right)\right] \quad (22)$$

where subscripts 0 and 00 present the reference condition and dead state condition, respectively. The exergy efficiency was computed by using

$$\psi = \frac{\sum m_{ex}\varepsilon_{ex}}{\sum m_{in}\varepsilon_{in}} \quad (23)$$

The obtained numerical value for exergetic efficiency was 55% while the exergy losses due to chemical reaction and heat transfer were reported to be around 44.5%.

The exergy analysis was applied to the refrigeration cycle of the natural gas liquid process by Mehrpooya et al. [46]. Exergy efficiency and losses were evaluated for each component. The overall exergy efficiency was reported to be 26.51% by using

$$Ex = \frac{\dot{E}_{out} - \dot{E}_{in}}{\dot{W}_{actual}} \quad (24)$$

Condenser and evaporator were detected as the main sources of exergy destruction [46]. Considering boiler as a combination of combustor and heat exchanger, the exergy of industrial boiler was evaluated by Saidur et al. [47]. It was pointed out that by neglecting the physical exergy, the chemical exergy of the fuels can be considered as the specific exergy [48]. The second law efficiency of the combustor was computed to be 45.18% by using

$$\psi_c = \frac{\dot{m}_p\varepsilon_p}{m_f\varepsilon_f} \quad (25)$$

where subscripts p and f represent the product and fuel, respectively. Applying Eq. (26), the exergetic efficiency of heat exchangers was evaluated around 48%.

$$\psi_H = \frac{\dot{m}_c(\varepsilon_s - \varepsilon_l)}{\dot{m}_h(\varepsilon_p - \varepsilon_g)} \quad (26)$$

The overall exergetic efficiency of the industrial boilers was reported to be 24.89% [47].

The energy and exergy efficiency of a cold thermal energy storage system was calculated by Rismanchi et al. [49,50], they found that generally, all cold thermal energy storage systems are highly efficient in terms of energy evaluation with the minimum almost 90%. However, the exergetic evaluation provides a more realistic picture for the process; the exergy efficiencies were reported far less than energy efficiencies, with a maximum value of 18%.

3. Future directions

There were a few works on exergy analysis of third world countries; applying exergy analysis to evaluate the performance of the industrial sector may lead to an energy consumption optimization and decrease the cost and emission. In most of the papers, cogeneration cycle was proposed as an alternative method to enhance the exergetic efficiency but an exoeconomic analysis can give a more realistic view to decide.

4. Concluding remark

Based on the reviewed literature, it can be concluded that

- There were significant differences between the energy and exergy efficiency of different industries and it determines the importance of second law analysis in performance optimizing of the industrial sector.
- Heating processes, steam generation and the extent that the studied industry depends on electricity are the main factors, which attribute the differences between the first and second law efficiencies.
- Comparing the energy efficiency analysis and exergetic efficiency of a system, it can be indicated that the exergy analysis provides more realistic picture considering the irreversibilities and potential optimization of the process.

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